EZwakeup: a sleep environment design for sleep quality improvement

Ming-Chun Huang
University of California, Los Angeles
420 Westwood Plaza
Los Angeles, CA 90095 USA
mingchuh@cs.ucla.edu

Jason J. Liu
University of California, Los Angeles
420 Westwood Plaza
Los Angeles, CA 90095 USA
jasonliu@cs.ucla.edu

Xiaoyi Zhang
University of California, Los Angeles
420 Westwood Plaza
Los Angeles, CA 90095 USA
stevezhanggeek@gmail.com

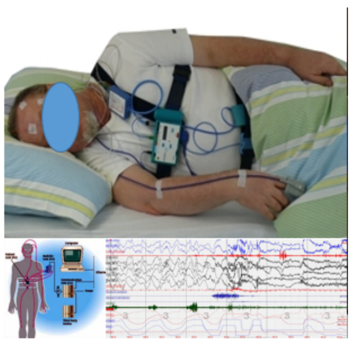
Majid Sarrafzadeh
University of California, Los Angeles
420 Westwood Plaza
Los Angeles, CA 90095 USA
majid@cs.ucla.edu

Wenyao Xu
State University of New York, Buffalo
Davis Hall
Buffalo, NY 14260 USA
wenyaoxu@buffalo.edu

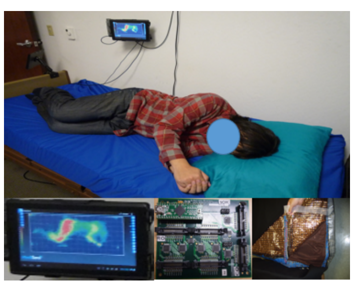
Abstract
Sleep quality affects people's work performance, mood, safety, and quality of life. Poor sleep quality reduces short-term memory, cognitive abilities, and motor skills for all age groups. We introduce EZwakeup, a system that extracts sleep quality indicators with an eTextile-based sensing system and applies feedback-guided external stimuli to smoothly wake people up from deep sleep. It can be directly deployed unobtrusively in home environments and does not require people to wear any external devices. In experiments, participants reported that they felt well rested and energetic for the rest of the day when they were awakened by the guided stimuli. This result suggests that EZwakeup might be a viable option for improving personal sleep quality and have potential in treating common sleep disorders.

Author Keywords
Sleep Stage; Sleep Quality; Polysomnography; eTextile; Guided Stimuli.

ACM Classification Keywords
H.5.m [Information interfaces and presentation (e.g., HCI)]: Miscellaneous.



(a) PSG Setup



(b) EZwakeup Setup

Figure 1: Comparison between Polysomnography (PSG) in a sleep lab and EZwakeup in a dormitory environment

Introduction

According to the statistics from the National Institute of Health (NIH) in 2005, it was reported that 70 million Americans suffered from chronic sleep loss or sleep disorders. Daytime sleepiness has affected people's working performance, caused car accidents, and reduced their regular social activities. More than one-third of adults reported that they had insufficient or poor sleep quality. NIH also indicated that sleep related disorders may lead to mental and physical diseases, such as anxiety, heart attack, and stroke. The annual cost for the relevant health care expenses is $16 billion in addition to $50 billion expense resulting from lost productivity [10].

This work aims to analyze the effectiveness of different stimuli in waking people through the right stage of sleep. The primary objective is to investigate whether stimulus intervention can affect the regular sleep cycle. The secondary goal investigates what type of stimulus is most effective. It is known that patients with sleep related problems improve their sleep quality by having good sleep habits. Sleep hygiene is the term that sleep experts use to refer to the practices resulting in good quality sleep, including having a regular sleep-wake cycle and avoiding caffeine late in the day [13]. In CHI, researchers investigated the potential in applying computer technologies to help people have healthy sleep habits [1]. Choe et al. [2] surveyed existing sleep-related technologies, presented the results of the interviews, and suggested the opportunity to improve people's sleep quality with unobtrusive solutions.

Sleep Quality Measurement

Common sleep quality measurement methods are polysomnography (PSG), actigraphy, and pressure distribution measurements. PSG uses encephalographic (EEG), electromyographic (EMG), and electrooculagraphic (EOG) sensors to quantify sleep stages. Using PSG systems usually means having people wear multiple delicate devices in a dedicated sleep laboratory environment. Although PSG is considered as the gold standard for sleep quality measurements, it is not convenient for daily sleep quality recording. A system called Lullaby was developed to record sleep conditions such as temperature, light, audio, and motion, around the sleeper [4] in order to analyze for trends or disruptions to sleep. In contrast with these previous research, our work uses unobtrusive ways to monitor biosignals.

Actigraphy, generated by sensors in smartphone, is more appropriate to be deployed in a daily sleep environment. An iPhone application, such as the Sleep Cycle Alarm Clock [6], provides real-time sleep stage recognition based on human body movements sensed by accelerometers. However, actigraphy quantifies the "restlessness" of an individual in bed and cannot detect which body part is moved and how it moves. Accelerometers may be able to capture breath signals, but the breath signal quality would be highly impacted by any delicate body movements or environmental noises. In addition to accelerometer based sleep behaviour measurement, pressure sensors are also used in extracting biophysical signals related to sleep quality. Kortelainen et al. [5], explored sleep stage identification methods with biosignals collected from 160 pressure sensors array. Due to lack of sufficient pressure image resolution, they considered all signal contributions equally and applied complex operations to extract heartbeat intervals and body movements from the pressure sensors. Our system is able to inconspicuously capture the type of motion of the body as well as respiration signals to infer sleep stage.

Stimuli Intervention

Researchers also investigated the effect of stimuli intervention on sleep quality. Sturm et al. [12] applied electric shock on patients with post-traumatic stress disorder before measuring their sleep quality. They reported that the electric shock intensity and extinction affected subsequent sleep architecture in young healthy subjects. Their results revealed that external stimuli would affect sleep quality, even though the stimuli was applied before sleeping. Lawson et al. [7] explored if mobile phone application can be used to influence sleep. They produced short 4-second low frequency (95Hz) low volume tone every 15 minutes to observe people's sleep condition changes. Their work showed the effect on stimuli intervention during sleep, but their interests was mainly on validating the actigraphy generated by mobile phone sensing, rather than understanding how to apply stimuli to improve sleep quality. Therefore, only constant volume and frequency tone were utilized in their study.

EZwakeup: System Overview

EZwakeup can be split into two parts: sensing and stimulus intervention. Figure 1 shows the hardware components of EZwakeup and Figure 2 shows a complete algorithm flow to extract sleep stages from time-indexed pressure image sequences generated by the eTextile sensor array and utilize the estimated sleep stages to control the frequency of the external stimuli, such as light, sound, and vibration.

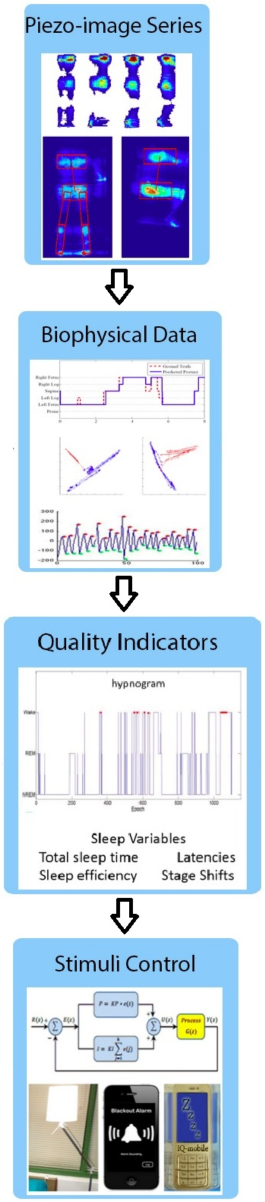


Figure 2: EZwakeup algorithmic flowchart from sensing to controlling

eTextile Sleep Sensor

In EZwakeup, an eTextile bed sheet consisting of 8192 pressure sensors (tunable sampling rate range from 1 to 10Hz) was used to record fine-grained pressure distribution of the 1.25m x 2.5 bed sheet. E-Textile is a piezoresistive material, similar to the fabric used in regular bed sheet, but it transforms imposed pressure into variable resistance. For example, the electrical resistance of the piezoelectric fabric decreases with increasing pressure force. The high density pressure sensor generates complete pressure profiles of the body. Sleep postures and body parts can be visually observed and extracted algorithmically as debriefed in the next section. With this detailed information, there is no restriction on how people lie on top of the bed. In addition, geometric information of the human body can be recorded, so that movements in sleep can be seen and tracked in the pressure image. An Android application was created to acquire the pressure data from the sensor unit of the bed sheet for storage and further analysis.

Algorithm Flow

EZwakeup extracts sleep information (sleep postures, body movements, and respiration signals) from static and dynamic pressure image sequences. Sleep postures can be reliably identified by using three sparse classifiers with 32 geometrical features as described by Liu et al. [8]. Six coarse-grained sleep posture categories were supported: supine, prone, left fetus, right fetus, left log, and right log. Slight difference in terms of extremities' location and orientation are included in the geometric information. A visualization of tracked torso and body parts are marked with red bounding box as shown in Figure 2. Three biophysical sample signals are plotted along with time in Figure 2 following sleep posture changes, body movements, and respiration signals. An overnight study of sleep posture changes are shown in blue, while the red plot indicates the ground truth. Body motions are tracked by a manifold learning technique, such as Local Linear Embedding (LLE). Different motion can be described by different manifold trajectories, which can be used to identify the transition of sleep posture changes and extremities movements [9]. For example Figure 2 shows four different trajectories of Leg Lift, Head Lift, Body Roll, and Sit up events. Respiration signals can be extracted from the pressure image sequences as well because chest rises and falls as people inhale and exhale. Fine-grained pressure images assist in localizing the interest area; therefore, the collected respiration signals is not easily affected by tiny extremities motion. In addition, aggregated pressure data are used, such as summation and standard deviation over interested area; thus, the collected signal are less sensitive to external random noises. Periodic respiration signals can then be identified by simple peak detection algorithm [3]. These features provide more versatile information served as sleep quality indicators compared with actigraphy; therefore, real-time sleep stage recognition among REM, NREM, and Wake states can be effectively recognized with simple machine-learning procedures. Samy et al. [11] compared the sleep stage recognition results with standard PSG system and showed good compliance in the overnight sleep monitoring experiments with 7 subjects. Figure 2 also depicts the sleep stage sample sequences in hypnogram. Sleep variables such as total sleep time, latencies, sleep efficiency, and stage shifts can be derived from the hypnogram and feed as inputs together with sleep stage information to the feedback-guided stimuli control. The stimuli controller has the ability to adjust the strength and frequency of the stimuli (light, sound, and vibration) based on the feedback of sleep quality indicators.

Stimulus control

Based on the categories of the sleep stages, people might be in REM, shallow, or deep sleep stage when the set wake-up time was close. Figure 3 shows a common sleep cycle pattern. An ideal wake-up moment should be in shallow sleep stage (Stage1 preferred). If the user is detected in deep sleep stage, EZwakeup emits stimuli with a repeated gentle but high frequency signal. The repeating frequency was inverse to the time interval of the wake-up time and the current time. When the subject is detected in REM stage, EZwakeup emits a gentle stimulus with constant low frequency signal. This is because REM stage is the time when people are in the dream state and might be sensitive to the external environment variance. Gentle and low frequency signals could slowly guide the sleep stage from REM to light sleep. When the set wake-up time came, if the sensed sleep stage is in the shallow sleep stage, the stimuli intervention emits a repeated high frequency and large strength signal (light, sound, or vibration).

Experiment Setup

We recruited 6 volunteers aged from 26 to 30 years old to participate in a pilot study of EZwakeup. Four of the participants were female and two of them were male. Their weights ranged from 110 to 180 pounds within the sensitivity range of the eTextile sensors. Each participant used EZwakeup for three non-consecutive nights. Three stimuli (light, sound, and vibration) were used respectively in each night for each subject following the same order. We interviewed each

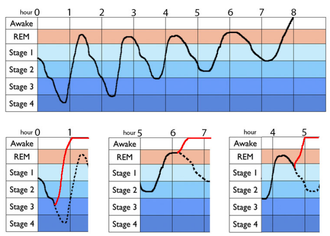


Figure 3: Three scenarios of smooth wake-up methods required

participant after their three nights study was completed to understand the usability and effectiveness of EZwakeup.

There were a few adjustments to the participants' bedrooms in the study. First of all, the eTextile sensor bed sheet needs to be placed underneath the participants' existing bed sheet. The data sampling controller was connected and powered by a tablet via USB connection. The placement of the tablet did not affect data collection. We simply put the tablet close to the bed end and turned off the tablet screen while the wireless connection was running and external stimuli control was tested. The external stimuli received bluetooth commands from the tablet. For example, an adjustable torchiere was placed on the bed head and a smart phone with a controllable audio and vibration loaded application was placed next to the pillow. There were no special devices required to be worn and no restrictions about sleep postures and movements for the users. Participants were advised to sleep as usual and keep their own regular sleeping hours.

Sleep Quality Improvement with Intervention

The primary goal of the study is to understand if stimuli intervention can effectively affect regular sleep cycle and allow users being awakened in an appropriate sleep stage, such as Stage 1. In tests, participants were generally happy with EZwakeup and reported that they felt well rested and energetic for the rest of the day when they were awakened by the stimuli intervention. All participants reported that they did not even feel the eTextile bed sheet sensors. Through examining the sleep stage changes, we observe that five of six participants had obvious sleep stage changes when stimuli intervention came; nevertheless, the changes caused by different stimuli source was different as discussed in the next section. One of the female participants did not think EZwakeup was effective for her. She reported that she felt that she woke up immediately when a stimuli was emitted. By examining her sleep pressure recording, we noticed that she always stayed in a shallow sleep and she did change from shallow sleep to wake stage as soon as the stimuli was activated. She provided a positive suggestion to encourage us to find out a different form of stimulus, such as music, to help people get into deeper sleep stages.

Sensitivity of Stimuli among Participants

The other study goal is to understand which stimuli intervention is more effective. Therefore, we let each participant undergo each stimulus one at a time and observed their sleep stage changes for different stimuli. In general, vibration did not cause clear sleep stage changes. Participants pointed out that the vibration on the phone was too weak to be felt. They only felt some vibration when they were awake. Therefore, we were prompted to use more powerful vibrators for the future experiment. Three of the four female participants (not the one reported that she did not feel EZwakeup helpful) reported that the light stimulus worked pretty well for them. They liked the feeling of having gentle lighting effect and the lighting variation made them more aware than the sunlight. Nevertheless, two male participants said that they felt that they were more sensitive to the sound. By investigating the collected data, we observed that these two participants had remarkable sleep stage changes when low frequency but gentle sound was played. Although we found some difference between male and female cases, the current pilot study scale is still too small to make such conclusions. Nonetheless, all participants who can get into deeper sleep stages reported that the unobtrusive sensing technology and stimuli intervention affects their sleep stages and promote their sleep quality.

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